The pathway to a national vascular skills examination and the role of simulation-based training in an increasingly complex specialty

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ABSTRACT

The evolving demands of surgical training have led to the successful implementation of skills examinations in the areas of laparoscopic and endoscopic surgery. Currently, there is no similar formal skills assessment in vascular surgery, despite endovascular intervention replacing open surgery in treatment of many vascular conditions. The adoption of less invasive techniques to treat aneurysm and occlusive disease has resulted in new training paradigms and technical challenges for trainees. The duty hour restriction for trainees and declining numbers of complex open vascular interventions have added to the challenges of vascular surgery training. Simulation is a promising avenue for both skills training and assessment. The ability to evaluate the fundamental skills of trainees would be an important step to ensure a degree of uniformity in trainees' technical abilities. The role of simulation-based training in acquiring, testing, and refining these skills is still in its infancy in the vascular surgery training paradigm. This article aims to impart a deeper understanding of the conditions for developing and implementing the fundamentals of vascular and endovascular surgery, and to provide guidance regarding the role of simulation-based training in a rapidly evolving specialty. There are various forms of simulation available, including benchtop models, high-fidelity simulators, and virtual-reality simulators, and each requires a different method of proficiency assessment. Both open surgery and endovascular skills can be assessed and the application of successful implementation in academic vascular surgery training program is presented.

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1. Introduction

Surgical education has experienced mounting pressure to train competent surgeons within the scope of decreasing work hours, increasing patient safety concerns, and mounting public scrutiny. Vascular surgery has been no exception and faces the additional challenges of a rapidly changing field in which new and evolving technologies have drastically impacted practice. The scope of pathology once relegated

entirely to open surgical management is shifting increasingly and exponentially toward endovascular interventions. The result is a field in which open operations are encountered less often by trainees, and those circumstances requiring an open procedure now involve highly complex and challenging cases. Meanwhile, new endovascular technologies are coming to market constantly, requiring users to learn new skills (both in training and beyond). The obvious answer to some has been the use of simulation as a means to both teach and test technical skills.

A current trend in surgical training is a move away from the traditional Halstedian apprenticeship model of graded responsibility to a more structured curriculum-based approach requiring documentation of proficiency [1]. Traditional resident educational paradigms have shifted due to changes in health care over the past several years. Mandated restrictions on resident work hours, shorter hospital inpatient lengths of stay, and the increase in outpatient surgery have led to a striking reduction in training opportunities for surgical residents. In the setting of quality-assurance targets, increased public scrutiny, and concern for health care safety, in addition to ethical concerns of "practicing" on patients, it is no longer acceptable, or appropriate, for residents at any level of training to practice novel skills on patients, even if they have a patient's explicit consent [2–6].

Concurrent with these trends and their impact on surgical training, dramatic technological advances have transformed the field of vascular surgery. New technology, devices, and techniques have pushed the specialty from a sub-field of general surgery into an entirely new area of expertise, with independent board certification and residency programs. Vascular surgery faces the additional challenges of a rapidly changing field in which technologies have drastically impacted the way the specialty is practiced. The scope of pathology once relegated entirely to open surgical management has shifted increasingly and exponentially toward endovascular interventions, as endovascular therapies are increasingly utilized to treat patients with peripheral vascular disease, abdominal aortic aneurysms (AAAs), and carotid artery disease [7–12].

The result is a field in which fewer open operations are performed, and those circumstances requiring an open procedure often involve highly complex and challenging cases unsuitable as training material, even for senior residents or fellows. This shift away from open operations has resulted in less experience with open vascular techniques for trainees, as well as a need to introduce catheter-based techniques to novice vascular surgical trainees during this same learning period [13–16]. Nevertheless, excellence in open surgical techniques is still required of surgical trainees, and incorporation of endovascular training into the curricula of vascular training is essential [17,18]. The changing skill set required of a vascular surgeon has been accompanied by paradigm shifts in vascular training. Residents can now enter a vascular surgical training program directly out of medical school. This model has become more popular over the past several years, and the number of programs offering the 0+5 training curriculum continues to increase. These integrated 0+5 vascular residencies pose new educational challenges, as residents entering the specialty have very limited or basic surgical skills and little to no endovascular experience.

In response to these external challenges and constraints, surgical skill and simulation centers have emerged at academic institutions across the United States. A consensus statement from the Society for Vascular Surgery, American College of Cardiology, and Society for Vascular Medicine and Biology published in 2005 encouraged simulation, stating that "In an effort to assist physicians with differing backgrounds and skills to reach a common benchmark of proficiency, metric-based simulation should be incorporated into training. This will provide skills acquisition in an objective manner, based on real-world situational experience" [19]. Surgical skills laboratories and simulation training allow for motor skills acquisition in a structured, low-stress environment that is free of adverse consequences to actual patients. Basic surgical skills are learned and practiced on models and simulators, with the aim of better preparing trainees for the operating room (OR) experience [20,21].

Simulators offer the ability to perform multiple procedures, while avoiding the real-life time constraints of anesthesia induction, room turnover, and paperwork. Additionally, simulation can allow novices to perform repeated attempts at the same intervention without risk to a human patient. Simulation also provides an excellent opportunity for error analysis and simulated management of procedural complications [22]. Used properly, simulation also offers economical use of training time, which is perhaps the most valuable resource to a surgical training program. Furthermore, there is mounting evidence that trainees, as well as vascular educators, increasingly support the integration of simulation into the training paradigm. In a recent survey of current trainees, 86% of respondents report that they believe there is educational value in simulation. Fifty-six percent of programs currently offer simulation training, most commonly in the form of peripheral endovascular simulators (70%), anastomotic models (58%), or endovascular aortic aneurysm repair simulation (53%), and more than one-third of current fellows and senior residents (37%) have attended outside simulation courses [23].

The implementation of simulation-based training for surgical trainees has evolved rapidly over the past few years. The increasing complexity of vascular surgery as a unique specialty that deals with the medical management, endovascular treatment, and open surgical repair of patients, should be ready to evolve along with these changes. Endovascular procedures lend themselves to simulation-based technologies much in the same way that laparoscopy does, because the three-dimensional to two-dimensional conversion of both approaches leads to an ease of developing high-fidelity images and anatomic-based simulation. Creating high-fidelity, responsive simulations of open operations, on the other hand, is more difficult to achieve. Nonetheless, vascular surgery has obvious applications for simulation-based technology.

This article will provide an overview of the results of available studies utilizing simulation to teach vascular techniques and discuss the potential benefits of using simulation in vascular surgery training. Additionally, it will review the

pathway to a formal vascular surgery skills examination, similar to Fundamentals of Laparoscopic Surgery (FLS) and Fundamentals Endoscopic Surgery (FES).

2.   Simulation-based training courses to teach vascular surgical skills

Vascular International, a school in Europe dedicated to providing supplementary training for vascular surgeons through short, intensive courses providing hands-on skills training (for both open and endovascular procedures), has been offering courses for more than 20 years. This model has been widely embraced in Europe, where work hours are limited to 48-hour weeks, as a means for trainees with insufficient operative exposure to gain experience. Furthermore, as training models vary widely throughout the European Union, these standardized teaching methods can ensure some measure of homogeneity in training. These techniques of standardized training have proven to be superior in a randomized study compared to traditional techniques, with the standardized group demonstrating improved technical scores (95% v 75%) and global rating scores (84% v 67%) [24]. These short training courses have also been shown to improve technical performance and quality on both carotid patch angioplasty and open aortic repair [25,26].

Following this model, weekend skills courses have been developed in the United States to address the needs and concerns of vascular faculty and trainees. At Houston Methodist Hospital, a 3-day intensive "bootcamp" for trainees from vascular surgery, cardiology, and interventional radiology, is held annually, and combines hands-on workshops and didactics, along with complex simulation exposure. This provides an opportunity to gain early experience with proven techniques in both open and endovascular scenarios [27]. While this course has been running for several years, it is not unique in its goal of exposing trainees to the benefits of simulation-based instruction. Several other state of the art simulation centers (eg, Center for Advanced Medical Learning & Simulation in Tampa, The Louisiana State University−LSU Health New Orleans School of Medicine Learning Center, and the Methodist Institute for Training Innovation and Education in Houston) host similar courses throughout the year. Likewise, major academic meetings (Society for Vascular Surgery's Annual Meeting, Society for Clinical Vascular Surgery's Annual Meeting, and EVEResT [European Virtual Reality Endovascular Research Team] Symposium) all offer hands-on courses to trainees that expose them to open surgical techniques, as well as the latest technologies in endovascular interventions, helping them to gain familiarity with new devices and techniques in both realms of vascular practice.

3.   Development of the fundamentals of vascular and endovascular surgery

Despite the demonstrable successes of the use of simulation for vascular training, it continues to be met with some degree of skepticism. In large part, this resistance is due to the fragmented way it has been developed and implemented. While most vascular surgery trainees now have some exposure to simulation-based training, a lack of standardization and availability of simulation-based models for all trainees persists. Compounding the problem is a lack of a practical curriculum for implementation of simulation-based methodologies. A major issue is the lack of structured performance assessment. Previously, the main way to assess a trainee was subjectively, the same method that has been in place since the advent of formal surgical education. The reality is that, along with new training paradigms and the ever-evolving field of vascular surgery, it is time that we define what comprises the essential skills for practicing vascular surgery. This idea is by no means a novel concept, having been adopted in general surgery with the FLS and FES programs.

With this in mind, a working group representing the Education Committee for the Association of Program Directors in Vascular Surgery began to determine the best approach for addressing these needs. Following the well-described path of our colleagues in general surgery through FLS and FES, we first set out to define a basic skill set for both open and endovascular skills. Over a period of several months, this team agreed upon a task list and then developed models designed to test those skills. From this start, the concept of the Fundamentals of Vascular and Endovascular Surgery was developed, which includes models for the Fundamentals of Vascular Surgery (FVS) and the Fundamentals of Endovascular Surgery (FEVS).

To derive a formal examination, such as the proposed Fundamentals of Vascular and Endovascular Surgery, to test the skills of vascular trainees, the role of simulation-based training in developing, refining, and mastering these technical skills must first be explored.

4.   Role of simulator use and discussion of various training models in vascular surgery training

Numerous simulation devices exist for vascular surgical training, each with its benefits and shortcomings. These models can be broadly characterized into five categories: low-fidelity synthetic, high-fidelity synthetic, animal, cadaveric, and virtual reality (VR). Endovascular procedures lend themselves to simulation technologies much in the same way that laparoscopy does, as two-dimensional imaging leads to an ease of developing high-fidelity simulation.

The earliest versions of synthetic models for vascular trainees came in the form of benchtop anastomotic models. These required only a stable platform, graft material, suture, and basic instruments. With these mock-ups, structured, low-risk practice could be performed, and was shown to be useful (primarily for junior residents) in improving skill [28]. Newer synthetic models range from simple to extremely high fidelity. Blood vessel anatomy can be synthetically simulated using devices from as simple as a plastic tube to complex multi-material sculptures (Fig. 1). Synthetic models can be inexpensive and are the most broadly available tools for vascular simulation. Synthetic models can also be created for endovascular use. Systems of pressurized tubes can be used to simulate stent placement and catheter manipulation.

Fig. 1 – Example of high-fidelity simulated synthetic abdominal aorta.

Fig. 2 – Procedure-specific trainers allow for simulation of a group of tasks of an operation or part of an operation in chronological order. These models are manufactured by Limbs & Things (Bristol, Avon, UK) and are used to practice open surgical skills, including saphenofemoral junction dissection and ligation, carotid endarterectomy, and aortoiliac aneurysm repair. Commercial companies (Limbs & Things, Bristol, Avon, UK) manufacture inanimate organ parts for saphenofemoral junction dissection and ligation, carotid endarterectomy and aneurysm repair.

We know from the aviation literature that level of simulator fidelity needs to be matched to stage of skill acquisition. Low-fidelity simulators (eg, synthetic models) are appropriate for early training (cognitive stage) of novice learners, whereas high-fidelity simulators are more appropriate for advanced and more experienced learners.

4.1.   *Low-fidelity models*

Low-fidelity simulations often use materials and equipment that are different from those of the actual task considered. Partial-task trainers have always been applied to open surgery in the most basic forms. These models consist of three-dimensional representations of body parts or body regions and provide functional anatomical landmarks useful for learning a particular skill. For example, plastic arms can be used for practicing venipuncture or blue phantom models can be used for practicing ultrasound-guided percutaneous access skills. These basic models allow novice learners to practice the individual tasks of a procedure. The downside of using these models is that the interface with the user is passive and procedures are performed with minimal response from the simulator [29].

Whereas partial-task trainers allow for simulation of a specific or individual skill, procedure-specific trainers allow for simulation of a group of tasks in the chronological order of

an operation or part of an operation. These models are usually made from silicon or rubber and contain various levels of realism. Examples include the models manufactured by Limbs & Things (Bristol, Avon, UK). These inanimate models are used to practice open surgical skills, including saphenofemoral junction dissection and ligation, carotid endarterectomy, and aortoiliac aneurysm repair (Fig. 2). These models are portable and easy to set up, but tend to be relatively expensive, as they can require replacement of their main components.

Low-fidelity partial-task trainers are also available for endovascular skills training. These benchtop models are relatively inexpensive (approximately $3000/unit) compared with the higher-fidelity models. They are effective for learning basic endovascular skills and allow for tactile force feedback to be experienced by the learner while using real wires, catheters, balloons, and stents. Unfortunately, one-time use of the equipment can be costly, adding to the expense of training, and these models lack realism and face validity.

A low-fidelity endovascular model, the Simulator for Testing and Rating Endovascular Skills, has been described recently [30]. This simple low-tech model consists of a light source covered by a container that holds a dry glass model of the abdominal aorta, renal and iliac arteries with various stenotic lesions, elongations, and tortuosities. The model does not require fluoroscopy, contrast, running water, balloons, or stents. A camera mounted above the glass model provides a view of the entire "abdomen" on a monitor (Fig. 3). Using
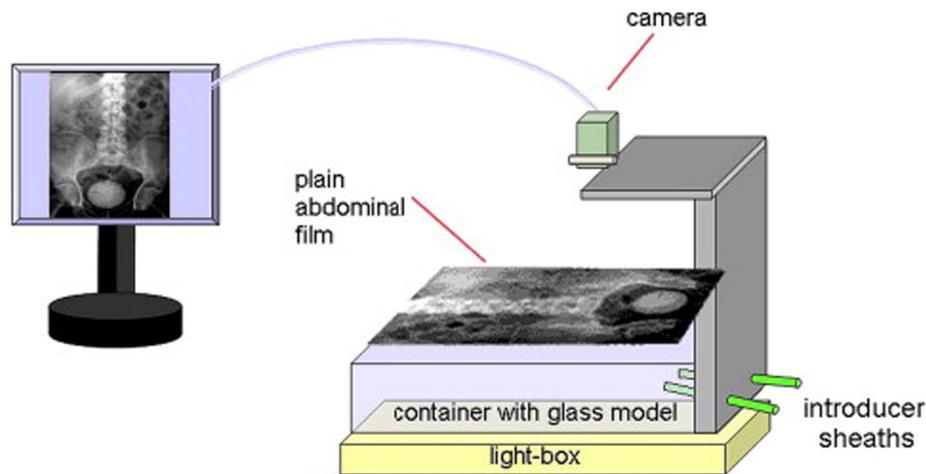
Fig. 3 – Schematic drawing of the Simulator for Testing and Rating Endovascular Skills machine, which consists of a light source covered by a container that holds a dry glass model of the abdominal aorta, renal, and iliac arteries with different tortuosities and stenoses. A camera placed above the glass model provides a view of the entire "abdomen" on a monitor. Using computer software, a plain abdominal radiographic image is merged with the live-camera feed, replicating a plain fluoro-mode. Introducer sheaths are prepositioned.

computer software, a plain abdominal radiographic image is merged with the live-camera feed, replicating a plain fluoro-mode, while blurring the few visible edges of the glass model. Real catheters and guide wires can be introduced into the introducer sheath prepositioned in the external iliac arteries. Wire and catheter skills can be practiced while looking at the computer screen, giving the impression of using fluoroscopy. Contrast angiography can be simulated in the live view, replicating a nonsubtracted, single-shot, contrast injection, which disappears after a few seconds.

4.2. High-fidelity models

An example of a higher-fidelity synthetic system is the pulsatile flow aortic model developed by Vascular International Foundation and School (Stansstad, Switzerland). Their open aortic model (Figs. 4 and 5) features a pulsatile flow system and a mock-up of abdominal contents. Using a replaceable aorta, trainees experience a realistic feel of the vessel wall when performing an anastomosis. The synthetic abdominal contents allow for the rehearsal of retractor and clamp placement. Another benefit of this system is the pulsatile flow, which allows for the identification of defects in the anastomosis. The main drawback of the model is price and limited portability, which may preclude daily use by trainees.

4.3. Animal models

Animal models offer a high degree of realism and animal laboratories are still employed for open and endovascular training. They can be used for teaching skills, such as iliofemoral angioplasty and stenting, as well as open aortoiliac artery replacement. Animal simulations also serve as test models for endovascular devices. Arterial stenosis and aneurysmal disease can be artificially induced through endothelial injury or sutured patches, respectively [31−33]. The use of animal models is limited by cost and other constraints. The

animal subjects require special facilities and instruments and have anatomic and size differences compared with humans. Furthermore, there are ethical and legal considerations with using animal models. Despite these limitations, large animal models do offer a highly realistic training opportunity for advanced interventions that cannot be simulated by a computer model.

4.4. Human cadavers

Human cadaver models provide realistic conditions for both open and endovascular training. As they have remained a mainstay in medical school education, they are also making a resurgence in surgical training as well. The American College of Surgeons and Association of Program Directors in Surgery have recently mandated incorporation of phase II modules into the surgical curriculum. A large majority of the modules include human cadaver dissection and practice of sentinel procedures. Cadavers, like animal models, have also been

Fig. 4 – Vascular International Foundation open aortic model.

Fig. 5 – Vascular International Foundation open aortic model.

Fig. 6 – The Procedius Vascular Intervention System Training (VIST) simulator comprises a mechanical unit housed within a plastic mannequin cover, a high-performance desktop computer, and two display screens. Modified instruments are inserted through the access port using a haptic interface device. Performance is measured using metrics such as volume of contrast used, fluoroscopy time, and markers of stent placement accuracy.

utilized to test endovascular devices. Garrett and colleagues [34] describe how pulsatile antegrade arterial flow can be established in the arterial system of a fresh human cadaver after a thrombolytic process. Endovascular procedures with standard arterial punctures and closures have been performed using this model. Fresh cadavers are the preferred model for teaching advanced vascular exposures, as synthetic models lack the fidelity required for advanced dissection. Restricted availability and cost limit the use of cadavers in training.

4.5. VR simulation

VR is defined as a computer technology that allows for a user to perform an operation or procedure in real time using a simulated three-dimensional system. VR simulation has been used extensively in high-stakes industries, such as the airline, nuclear, and oil industries. In the aviation industry, it has been effective in providing pilots with a means of training without actually flying an airplane [35–37]. Successful utilization of simulation in aviation ultimately led to the development of simulation programs applicable to minimally invasive surgery, with Satava [21] first proposing the use of the surgical simulator in 1993.

Endovascular therapy poses technical challenges like those experienced in minimally invasive surgery, including reduced tactile sensation and the need to overcome the proprioceptive-visual issues of working in a three-dimensional field displayed on a two-dimensional fluoroscopy screen. Several endovascular VR simulators are commercially available and include the Procedicus Vascular
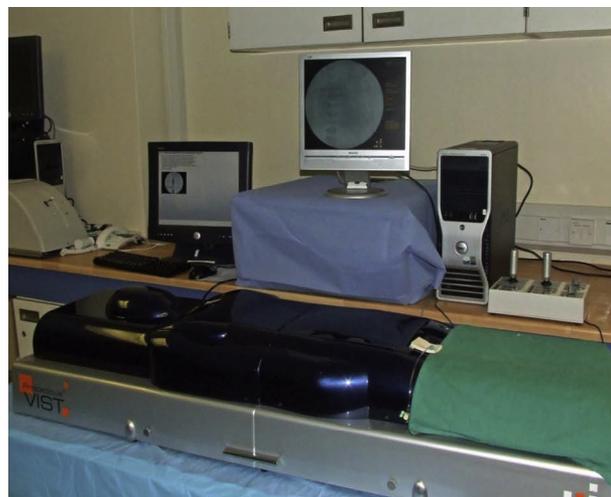
Intervention System Training (VIST) simulator (Mentice AB, Götenborg, Sweden), the ANGIO Mentor (Simbionix, Cleveland, OH), and the SimSuite (Medical Simulation Corporation, Denver, CO). These high-fidelity simulators include haptic, visual, and aural interfaces that provide near realistic representations of the actual procedure. These simulators provide a variety of training applications and include modules for angioplasty and stenting of the carotid, renal, coronary, superficial femoral, and iliac arteries. More recent technology has allowed for simulated aortic aneurysm repair, neuro-interventions, closure of patent foramen ovale, deployment of a caval filter, and implantation of cardiac pacemaker leads.

The Procedicus VIST simulator comprises a mechanical unit housed within a plastic mannequin cover, a high-performance desktop computer, and two display screens (Fig. 6). Modified instruments are inserted through the access port using a haptic interface device. Commercially available simulation modules can mimic arterial occlusive disease in the coronary, carotid, renal, and ileo-femoral regions and over the wire lead placement for biventricular pacing. The learner selects appropriate instruments to perform virtual interventional procedures using the simulated fluoroscopic screen. Performance is measured using metrics such as total procedure time, fluoroscopy time, and markers of quality of performance, such as stent placement accuracy (Table 1).

The ANGIO Mentor Ultimate endovascular trainer has a similar range of arterial procedures as the VIST. It differs from the VIST in that there is greater emphasis on patient monitoring, drug administration, and response to physiologic disturbance. For example, Atropine can be administered to correct for bradycardia related to simulated carotid sinus stimulation. Appropriate therapies can also be provided for hypoxia and hypertension. This device allows for simulated

Table 1 – Comparison of virtual reality endovascular trainers.

Device	Description	Modules	Assessment parameters	Validation studies
Procedius VIST	Part procedure simulator Haptic feedback Metric assessment	Neuro interventions Coronary Carotid Renal Iliac/SFA	Quantitative metrics Qualitative metrics Clinical parameters Technical errors	Face validity Construct validity Transfer of training
ANGIO Mentor	Part procedure simulator Haptic feedback Neurologic and pharmacologic responses Metric assessment	Coronary Carotid Renal Iliac/SFA	Quantitative metrics Qualitative metrics Clinical errors Hemodynamic features Handling of complications	Ongoing studies
SimSuite	Part procedure simulator Haptic feedback Neurologic and pharmacologic responses	Neuro interventions Coronary Carotid Renal Iliac/SFA Closure patent foramen ovale	Quantitative metrics Qualitative metrics Clinical parameters Technical errors Hemodynamic features Handling of complications	Training study Ongoing studies to determine construct validity and benchmark performance

Abbreviations: SFA, superficial femoral artery; VIST, Vascular Intervention System Training.

complications to occur so that management of the complication can be practiced in a virtual environment. Two more affordable and portable versions of the simulator are also available, the ANGIO Mentor Express and ANGIO Mentor Mini (Figs. 7 and 8). These devices have a similar simulation package with less peripheral attachments, such that the Mini can be transported in a hand-held case.

The SimSuite is a larger simulator system with up to six interactive screens to facilitate multidisciplinary team training (Fig. 9). This system provides multispecialty training packages and personnel to support the training program. These simulators allow for pre-procedure briefing, patient intervention, and post-procedure analysis. Similar to the ANGIO Mentor system, response to patient physiology is a feature of this simulator.

VR simulators have an advantage over low-fidelity simulators in that they have software capable of providing metric feedback. Learner's skill can be objectively assessed and output metrics can be used for evaluation and feedback of trainee progress. This provides an avenue for both self-directed learning and curriculum development. Some endovascular simulators also allow for surgical planning. Specific anatomic details of the patient from radiologic images can be installed into the simulator computer, and the planned procedure rehearsed on the simulator before performing on the patient. VR simulators have the added advantage of re-use ad infinitum and have no associated ethical issues related to their use.

There are, however, several limitations to using VR simulators for endovascular training. The most obvious is the high cost of the simulator. Most of these devices cost more than $100,000 for a single unit and many additional thousands for maintenance over time. Endovascular simulators require regular maintenance and housing space. The need for constant software updates and calibration often necessitates a full-time technician to manage technical failures, regular

Fig. 7 – The ANGIO Mentor platforms: The ANGIO M*entor Ultimate endovascular trainer has a similar range of arterial procedures as the Procedius Vascular Intervention System Training (VIST) with more advanced haptic technology. The ANGIO Mentor Express and ANGIO Mentor Mini have similar simulation packages but with less peripheral attachments, such that the Mini can be transported in a hand-held case.

Fig. 8 – The ANGIO Mentor superficial femoral artery and Iliac module allows trainees to choose either ipsilateral or contralateral access approach according to their preference and the morphology of the vasculature.

calibration, and maintenance and updating of required software. In the current setting of vascular surgical training, with multiple vascular trainees at a given institution at one time, it may be hard to justify the expense of a VR simulator, given concerns about the limited data to support their validity and transferability.

One proposed lower-cost alternative is to set up regional centers where residents could travel periodically for short training sessions [38]. Current training is also limited by challenges in unrealistic tactile feedback and graphical interfaces. Significant improvement in haptic response and realism of the virtual environment is still needed. Until the realism and the high cost of these simulators improve, it will be difficult to transition these devices out of the research laboratories and into training programs. Finally, these devices are still partial-task simulators, as they cannot always teach some of the important skills associated with endovascular cases, such as arterial puncture and closure.

5. Methods of assessment of technical competency in vascular surgery

Traditionally competency in surgery has been defined as completion of a defined length of training or number of cases.

Fig. 9 – The SimSuite simulator provides tactile "haptic" feedback and displays real-time imaging and physiologic information.

This is now true for endovascular procedures as well [39]. Other than some skill laboratory incorporation, there are currently no clear guidelines from the Accreditation Council for Graduate Medical Education (ACGME) regarding simulation training in vascular surgery. Additionally, no US specialty board accepts simulation experience as a proxy for patient case logs. Operative log data lack content validity, as they only indicate volume of operations performed and do not capture procedural understanding, participation, or performance level. As such they are recognized to be an unreliable and indirect measure of technical skill [40,41]. It has also been demonstrated that no correlation exists between an individual's operative experience as reported by case logs and their technical performance [42]. The number of procedures performed and time in training does not automatically equate to expertise. As a result, vascular residencies need to move toward objective assessment tools to demonstrate technical competence.

Formal testing of surgical dexterity is not a modern concept. Fellowship in the Royal College of Surgeons required a technical skill examination through the early 1940s. In the United States, the American Board of Surgery conducted intraoperative assessments on prospective candidates through 1952. Both practices were halted due to logistical problems, such as time, cost, and standardization.

Furthermore, in a prospective randomized trial, residents' scores on the multiple-choice American Board of Surgery In-Training Examination did not correlate with their technical ability measured by either skill testing or intraoperative assessment [43]. This supports the findings of a pilot technical skill assessment conducted with the European Board of Surgery Qualification in Vascular Surgery examination in 2002. European candidates performed a saphenofemoral junction ligation and a tibial artery anastomosis on open models. Additionally, dexterity was assessed with a knot-tying test. Internal consistency was demonstrated among the three technical examinations, but the study found no correlation between technical ability and the candidates' scores on an oral knowledge examination. Currently, the multiple-choice Vascular Surgery In-Training Examination is the only standardized test given during vascular surgery training, and no standardized method exists for surgical skill evaluation.

Written and oral examinations, the established markers of surgical competence, assess knowledge base and clinical reasoning only, and do not evaluate technical performance or nontechnical skills critical to managing an operation or crisis scenario. In most programs, direct observation has been the only assessment tool utilized for the appraisal of technical ability. Simulation-directed surgical skill testing offers a potential solution to these issues.

Observer assessments can be performed with checklists, global assessments, or some hybrid method. Methods of assessing performance and improvement in performance in a surgical skill are essential to the development and implementation of a vascular surgical skills laboratory. Objective measures of skills performance utilized in skills training will be discussed.

5.1. Time-action analysis

At its simplest, a scoring system for skills training may include time and errors. Time-action analysis has been used extensively as a method of objective assessment of performance in open and minimally invasive surgery [44−46]. The method can be applied to real life or simulator performance and involves breaking the procedure down into a series of steps with performance analyzed by how long the learner takes to complete the task [47,48]. This procedure is very personnel- and resource-intensive because of required setup and video analysis. Decreased time to perform the task may indicate progression of skill, but the amount of time taken to complete the individual procedural steps does not, in and of itself, offer any measure of the quality of the performance. Therefore, time-action analysis may require supplemental markers to fully assess the progression of skills.

5.2. Error analysis

The 1999 National Academy of Science Institute of Medicine report, *To Err is Human*, raised awareness of patient safety issues [49]. "Error in the performance of an operation" was cited as one of the leading causes of patient deaths in hospitals. The uncontrolled introduction of laparoscopic cholecystectomy made the public and surgical community more aware of the implications that surgical training could have on patient safety [50]. Cost issues related to surgical complications have made third-party payers keenly aware of training and surgeon competency; as a result, human reliability and error analysis is now an evolving field in health care.

Error scores have been proposed as discriminators of technical skill, though inherent difficulties exist in defining surgical or medical error, as there is no standardized taxonomy [51]. It is, however, possible to differentiate technical skill by examining both the frequency and type of error committed during laparoscopic cholecystectomy and pyloromyotomy [52−54]. To date, error analysis in endovascular training and assessment is at an early stage with no reported studies examining this question in vivo. Modern simulator technology allows reporting of catheter and device handling errors. Patel et al [55] reported a reduction in the composite catheter handling error

scores of interventional cardiologists performing a virtual carotid angiogram following simulator training.

5.3. Motion analysis

Motion analysis may offer a less time-consuming option. Efficient and purposeful hand movements are a discriminator of technical skills in surgery [56]. The technology is already available, and indeed surgical dexterity is currently assessed using this modality for the open surgery portion of the European Board of Surgery Qualifications in Vascular Surgery examination. The Imperial College Surgical Assessment Device is used to track hand movement in three-dimensions using electromagnetic sensors with a composite score based on economy of motion and qualitative analysis [28]. Clearly, this technology is associated with significant cost. Nonetheless, this is a potentially exciting area for future research in the open vascular and endovascular arena.

5.4. Objective Structured Assessment of Technical Skills

Beyond simple metrics, a rating of technical performance by expert observers remains an important assessment tool. In 1996, at the University of Toronto, Faulkner and colleagues, under the direction of Richard Reznick, introduced the Objective Structured Assessment of Technical Skills (OSATS). A global rating scale is a quantitative assessment tool based on an appraisal of seven aspects of quality in operative performance. Each component is evaluated on a 5-point grading scale. The items included respect for tissue, time and motion, instrument handling, knowledge of instruments, use of assistants, flow of operation/forward planning, and knowledge of the specific procedure [28]. This method has been demonstrated to differentiate between experience levels in both open and minimally invasive surgery [57−60].

A modified global rating scale has been shown to differentiate endovascular experience and training using a VR simulator. Hislop et al [61] have proven the construct validity of an OSATS-derived Modified Reznick Scale for post-hoc video-based rating by two blinded observers during a virtual selective carotid angiography. The first two studies examining VR transfer of training to the catheterization laboratory both used the modified rating scales [62,63]. Tedesco et al [64] have demonstrated that a single blinded expert observer was able to discern differences in endovascular experience during a virtual renal artery stent procedure using a structured global rating scale. Although the EVEResT study included only experienced interventionalists, those who scored high on the OSATS-derived generic rating scale were more likely to be experienced in carotid angioplasty and stenting (CAS) [65].

Procedure-based assessments possess high inter-rater reliability (G > 0.8 using three assessors for the same index procedure), excellent construct validity, and positive user satisfaction and acceptability (trainees and reviewers). The tool, however, is very procedure-specific and long (checklist of up to 62 items), which limits its practicality for use in evaluating common but increasingly complex hybrid open and endovascular procedures.

Procedure-specific checklists used in conjunction with global rating scales have been shown to be effective and reliable assessment tools of surgical dexterity using synthetic and cadaveric models, as well as in live operations [66,67]. Posthoc video-analysis, though not mandatory, does reduce the potential for bias. The main disadvantage of this mode of assessment is that a large amount of time is required from expert assessors. Full-length video viewing is required as edited video assessment appears to reduce reliability [68]. Based on a systematic review of methods of assessment, checklists and global rating scales presently appear to be most accepted as the "gold standard" for objective technical skills assessment. Their use in the OR, however, has been limited partly due to the variability of operative procedures (ie, they do not all conform to a standardized checklist), the time required for completion of these tools, and faculty familiarity with these tools and their application. Furthermore, benchmark levels of performance for these assessments have not been defined. While these shortcomings should not prevent their use for formative assessment (assessment for learning, ie, feedback and discussion), they may prohibit use for high-stakes examinations (summative assessment).

5.5. VR simulators

The major advantages of VR simulation are the ability to automatically and instantly provide an objective performance report based on quantitative and qualitative assessment parameters. Error scores and rating scales can be used in combination [61,62,69]. Used in a standardized setting, it is possible to distinguish between subjects of different levels of experience [70−72]. Assessment of nontechnical skills, such as appropriate drug administration and physiologic monitoring, is also possible with most of the current generation of simulators.

The validity of this method of assessment is under evaluation as discussed previously. Currently, performance reporting remains unsatisfactory, quantitative measures of performance related to procedure time and use of the c-arm are well reported, but further work is necessary for developing more subtle indicators of performance and judgment, such as clinical outcome and technical error. Though further work is required, simulation-based assessment is potentially a mechanism for selecting candidates for surgical or interventional training programs and may be a requirement for recertification or gaining credentials to perform procedures [73].

5.6. Relationship between nontechnical skills and OR performance

While not actual measures of surgical performance, self-reported operative competence and stress levels appear to be important markers of coping ability. The evidence suggests that effectively coping with stressful events in the OR has a beneficial impact on technical skills performance [74]. Similarly, the relationship between nontechnical (communication, decision-making, situational awareness, and leadership skills) and technical performance in the OR is strong, and it is now widely reported that deficiencies in teamwork, rather than simply poor technical ability, contribute more commonly to adverse events in the OR [74].

6. Evidence for simulation in open vascular skills training

The earliest forms of vascular simulation-based training for surgical trainees came in the form of benchtop anastomotic models. Requiring only a stable platform, graft material, suture, and basic instruments, structured, low-risk practice could be performed. There is evidence for the benefit of these simulations in improving open technical skills, particularly for junior residents [28,75]. These simple models, however, failed to capture the interest of senior residents and fellows, as well as faculty, as their fidelity is limited. So while simple tasks, such as suturing an anastomosis, are adequately replicated by these simple models, more complex skills, such as dissection and exposure, require advanced models. As work-hour reductions and growing endovascular options for traditionally open surgical techniques began to limit trainee exposure, a role for more complex vascular simulation models presented itself.

In response to growing concerns that trainees simply were not exposed to enough volume of open surgical cases, high-fidelity, pulsatile flow models were developed to allow for a standardized training platform. These pulsatile flow and other open surgical models have been incorporated into courses to train vascular surgeons, as described later in this article.

Sidhu and colleagues [76] from the University of Toronto have demonstrated that laboratory training does improve basic vascular skills. Acquisition of skill was significantly affected by model fidelity and level of training as measured by checklist and final product analysis. Practice on high-fidelity models (cadaver brachial arteries) improved skill acquisition for both junior and senior residents learning vascular anastomosis techniques, as compared with low-fidelity models (plastic tubing). This was the first study to address the combination of the effects of level of training and model fidelity on skill acquisition. These findings conflicted with previous studies performed at the same institution that demonstrated equivalency of low- and high-fidelity models for plastic surgery and urology procedures [75,77]. This work suggests that there is more benefit in using higher-fidelity models for more experienced learners. In other words, for optimal motor learning, the level of difficulty during the skill acquisition must be adjusted to the learner's current expertise level.

A saphenofemoral junction model was used by Wolfe and Darzi to assess the surgical competence of learners with all levels of experience, from senior house officers to experienced consultants, by using the Imperial College Evaluation of Procedure-Specific Skill rating scale in conjunction with the OSATS global rating scale [78]. The saphenofemoral junction groin model (Limbs & Things) depicted the human saphenofemoral junction and its tributaries. This model allows for incision of the skin and dissection through the superficial fatty and deeper fascial layers. The fluid-filled long (greater) saphenous vein and its four groin tributaries can be identified, ligated, and the saphenofemoral junction disconnected. This investigation showed that surgical performance continues to improve significantly beyond training. Importantly, this study also demonstrated the construct validity and high inter-observer reliability of the Imperial College Evaluation of

Procedure-Specific Skill rating scale, supporting its use in formative and summative assessment.

Carotid endarterectomy is an operation where technical errors can be associated with substantial risk. A synthetic benchtop model (Limbs & Things) has been developed in conjunction with St Mary's Hospital, London, UK. This model consists of a plastic box and supporting structures with a replaceable latex carotid artery containing adherent plaque. Black and colleagues [79] demonstrated that this bench model is a valid tool for the evaluation of basic technical skills in the performance of carotid endarterectomy. Use of the model in a simple, easily reproducible benchtop environment discriminated between junior and senior vascular trainees by both evaluations of video performance and end-product scores. The model, however, failed to discriminate between senior trainees and consultant surgeons, with these two groups performing at the same level in all assessments. These results demonstrate the inherent weakness of using benchtop models for training or assessing more advanced learners. Decision making, judgment, situation awareness, and leadership skills were not evaluated in this situation. More complex simulations, that is, simulated operating rooms, may be needed to discriminate between more senior trainees and attendings.

Simple models allow the basic steps of a procedure to be taught to trainees in a nonpressurized environment where the patient is not at risk. Use of the carotid endarterectomy model allows for acquisition of the basic skill components of the procedure (order of the clamp placement and removal, site of the arteriotomy incision and basic considerations of the endarterectomy) before moving to the OR. In addition, video review has the advantage of identifying errors in performance that can be demonstrated to trainees, providing valuable feedback [26,80].

Because of the previously noted trend toward preferential endovascular repair, the prevalence of open aortic surgery is significantly decreasing. Records from Medicare beneficiaries from 1995 to 2008 and ACGME records from 1999 to 2008, demonstrated that the average annual number of open AAA repairs performed by vascular fellows decreased from 44.1 to 21.6 in this time period. Also noted was a concomitant increase in endovascular repair of AAA with approximately 78% of AAA repairs in 2008 done by endovascular aneurysm repair [81]. The efficacy of simulation training for open AAA repair was investigated by Robinson et al [82]. They randomized a group of senior residents to one of two simulation training sessions. The first was performed with vascular attending oversight and the second session was an identical course conducted with a skills laboratory coordinator. The authors reported that the less experienced residents demonstrated greater improvement after simulation training and that those mentored by a vascular attending had significant improvement in overall operative competence, but those overseen by a skills laboratory coordinator did not. Their primary conclusion was that simulation training efficacy was dependent on vascular staff involvement. The study was not, however, able to demonstrate that improvement in the simulation laboratory correlated with improvement in the OR.

In 2012, Mitchell et al [83] published a report in which 24 senior general surgery residents attended five structured 4-hour cadaver skill sessions. In these lessons, the residents performed five different vascular exposures, including the supraceliac aorta exposure. Trainees were tested pre- and post-lesson via an oral examination and a self-confidence report. Significant improvement was seen in both the mean oral examination scores ($P < .001$) and the mean operative confidence scores ($P < .001$) for each individual exposure. These studies aid in suggesting that there is benefit from simulation of open aortic surgery in trainees, as it increases exposure, experience, and confidence.

7.   The evidence for simulation in endovascular skills training

When first introduced, endovascular simulation was a largely industry-driven means of introducing interventionalists to new endovascular devices and techniques using VR simulators. CAS was identified as a high-risk procedure with potentially devastating consequences for patients, where VR simulators could help mediate good outcomes. To meet this need, VR simulation was developed to allow users to be trained on a safe platform. Similarly, to be approved for use of a device by industry, simulation-based practice was required for thoracic and abdominal endovascular repair. Several validation studies were published to demonstrate the utility of this approach. These studies confirmed that performance improved with standardized simulation-based practice [84,85]. Based in part on these findings, a 2005 consensus statement from the Society for Vascular Surgery, the American College of Cardiology, and the Society for Vascular Medicine and Biology encouraged the use of simulation-based training, stating that "In an effort to assist physicians with differing backgrounds and skills to reach a common benchmark of proficiency, metric-based simulation should be incorporated into training. This will provide skills acquisition in an objective manner, based on real-world situational experience" [19].

VR simulation for endovascular interventions was rapidly developed for the breadth of vascular interventions from aortic, to mesenteric, and lower extremity intervention. Numerous studies evaluating validity and utility of endovascular simulation were carried out, and, across the board, results supported the utility of endovascular simulation-based training. Participants improved their performance on the simulated procedures for aortic, renal, lower extremity, and carotid interventions as measured by global rating scales, procedural checklists, and procedural metrics (ie, task completion time, fluoroscopy time, contrast use) [86−88] and, in select studies, these improvements translated to skills demonstrated on a live animal model [63,71]. These encouraging findings have led many vascular surgery programs with adequate funding to make the large investment (>$200,000) in VR simulators. However, many programs cannot afford that expense, making standard implementation of VR simulation into the curriculum unrealistic.

Driven by the need to validate endovascular VR training, three specialties involved in the endovascular treatment of vascular diseases in Europe have joined forces as the European Virtual Reality Endovascular Research Team (EVEResT).

The goal of this group is to improve training of the present and future endovascular therapists through combined research and curriculum development. It is understood that before endovascular simulators can be universally applied to vascular training programs, demonstration of reliability, feasibility, and validity is necessary. It is incorrect to assume that a realistic simulation equates to an effective training or assessment model [83,89].

Perhaps more than in any other vascular bed, simulation can play a vital role in instructing interventions in the cervical carotid circulation and therefore deserves special attention here. Because carotid interventions provide a small absolute risk reduction, even a rare technical error can override a surgeon's margin of efficacy. Additionally, small missteps during a carotid stent placement can result in severe morbidity and even mortality. These procedures must be assiduously learned before attempting independent performance. There are few true high-volume centers, however, and a paucity of experts to train novices. In the United States, multi-specialty consensus statements issued by the American College of Cardiology, American College of Physicians, Society for Cardiovascular Angiography and Interventions, Society for Vascular Medicine and Biologym and the Society for Vascular Surgery provide recommendations on the training and credentialing for CAS and other catheter-based interventions [19,90]. This statement reflects a recent worldwide shift in focus toward outcomes-based education throughout the healthcare professions. This paradigm change derives in part from attempts by academic institutions and professional organizations to self-regulate and set quality benchmarks, but chiefly it represents a response to public demand for assurance that doctors are competent [34].

This stance was adopted by the Food and Drug Administration (FDA) with the approval of a CAS system in August 2004 [91]. The FDA supports the use of simulation training as a component of physician training for CAS. Another requirement of the FDA approval for CAS was the initiation of a post-marketing surveillance study to assess the safety of the new device in everyday use and to assess its safety in the hands of operators with varying levels of experience. Two such post-marketing surveillance studies provide promising results [92,93]. These studies evaluated the performances of experienced endovascular physicians who sought to learn a new procedure by using short-training courses.

7.1. Validity

An overview of the published papers that have sought to support the validity of various modules of computer-based simulators is provided in Table 2 [61–64,69–72,85–87, 94–102]. Most research has been conducted using the Vascular Intervention Surgical Trainer (VIST; Mentice, Gothenburg, Sweden).

Patel et al [69] revealed that participants of the Guidant CAS 2-day regional training course using the VIST simulator had improved performance across five test trials as assessed by the metrics (catheter handling errors, procedure time, fluoroscopy time, and contrast volume). This study represents the largest collection of such data to date in carotid VR simulation and is the first report to establish the internal consistency of the VIST simulator and its test–retest reliability across several metrics. These metrics are fundamental benchmarks in the validation of any measurement device. Composite catheter handling errors represent measurable dynamic metrics with high test–retest reliability that is required for the assessment of high-stakes procedural skills.

A supervised 2-day virtual CAS training course for experienced endovascular physicians on the ANGIO Mentor simulator provided similar results. Post-course interventions were performed faster, with less radiation, and with fewer catheter handling errors. Spasm of the internal carotid artery occurred less frequently. Post-hoc ratings by two experienced CAS physicians showed excellent inter-rater reliability, reduction in number of observed errors, and an increase in quality of performances when comparing the group's pre- and post-course performances.

Dayal et al [71] evaluated the use of simulation to train novice and advanced interventionalists in CAS. After didactic instruction, each participant performed CAS, followed by training on the VIST simulator and performance of a second graded CAS. Participants had reduced procedural and fluoroscopic time, and improved wire and catheter techniques. These results were consistently better for experts than novices. This supported the construct validity of the simulator, as it can accurately reflect the skill of the individual.

Hsu et al [94] conducted a similar randomized trial comparing the performance of CAS by skilled and untrained interventionalists. After a pretest, participants were randomized to receive supervised practice on the Procedicus VIST simulator, or no practice. Procedural time and successful completion improved significantly and correlated with previous experience, thereby supporting the construct validity of the simulator. Most of the participants rated the simulator as realistic with good force feedback supporting face validity. These participants also agreed that training on endovascular simulators should be mandatory before performing CAS in actual patients.

Studies carried out by the EVEResT group differed from these two studies. Only physicians with the basic endovascular skills and appropriate medical background to treat carotid artery stenosis were included [70,85,87,99]. Experienced interventionalists were found to have shorter procedural and fluoroscopic times, and improved wire and catheter techniques for CAS. These findings confirm the ability of the simulator to accurately reflect the skill of an individual, again supporting its construct validity [61,70–72,85,87,100,101].

7.2. Learning curve

The term learning curve used in the context of skills training refers to the time taken and the number of procedures an average practitioner needs to be able to perform a procedure independently with an acceptable outcome [103]. Learning curve can be measured by patient outcomes (morbidity or mortality) or via procedure-specific metrics (blood loss and operative time) [104]. Mastery of the clinical tasks of an

Table 2 – Overview of virtual reality endovascular assessment and training studies.

Study, first author, year	Simulator device	Module	Face validity	Construct validity	Training potential	Transfer of training to in vivo
Wang [72], 2001	Accutouch	Cardiac lead placement	—	Yes	—	—
Dayal [71], 2004	VIST	Carotid	Yes	Yes	Yes	—
Hsu [94], 2004	VIST	Carotid	Yes	Yes	Yes	—
Nicholson [95], 2006	VIST	Carotid	Yes	—	—	—
Aggarwal [6], 2006	VIST	Renal	—	Yes	Yes	—
Hislop [61], 2006	VIST	Carotid	—	Yes	—	—
Berry [96], 2006	VIST	Renal	Yes	No	—	—
Patel [69], 2006	VIST	Carotid	Yes	—	Yes	—
Chaer [63], 2006	VIST	Iliac/SFA	—	—	—	Yes
Passman [97], 2007	SimSuite	Iliac/renal/carotid	Yes	—	Yes	—
Dawson [86], 2007	SimSuite	Iliac	Yes	—	Yes	—
Berry [62], 2007	VIST	Iliac	Yes	—	Yes	Yes
Neequaye [98], 2007	VIST	Iliac/Renal	—	—	Yes	—
Van Herzeele [87], 2007	VIST	Carotid	Yes	Yes	—	—
Van Herzeele [85], 2008	ANGIO Mentor	Carotid	Yes	—	Yes	—
Tedesco [64], 2008	VIST	Renal	—	No	—	—
Van Herzeele [99], 2008	VIST	Iliac	—	Yes	—	—
Berry [100], 2008	VIST	Carotid	—	Yes	—	—
Glaiberham [101], 2008	VIST	Renal	—	Yes	—	—
Klass [102], 2008	VIST	Renal	—	—	Yes	—

Abbreviations: SFA, superficial femoral artery; VIST, Vascular Intervention System Training.

endovascular procedure often follows a steep learning curve; this has obvious implications for patient safety, particularly when novices are performing invasive procedures on real patients.

Lin et al [105,106] analyzed the outcomes of sequential groups of patients undergoing CAS and demonstrated decreased procedure-related complications, fluoroscopic time, and contrast volume used with increased experience. Simulation-based training may allow the early part of this learning curve to take place without exposing patients to unnecessary risk. Other studies examining the potential for using VR systems in endovascular skills training have analyzed the learning curves of both novice and expert subjects. Results are mixed. Dayal et al [71] demonstrated improved simulated performance of CAS procedure by novice subjects. Expert performance was not improved following training. Hsu et al [94] showed significant improvement in both novice and expert subjects. Aggarwal et al [70] analyzed the learning curves of experienced open vascular surgeons and demonstrated improved performance (procedure time and contrast used) after VR simulator training using a renal artery stenting model. A second study from this unit showed that while there is an expected learning curve in performing endovascular tasks, endovascular skills were widely applicable and, once learned, these skills could be readily transferred between different simulated procedures [99]. Similar improvements in simulator training have been reported for iliac and renal angioplasty [86,98].

These training studies suggest that repetitive practice with the endovascular simulator benefits the novice learners more than the expert subjects. Learning curves are shortened as the novice becomes more familiar with the simulator. Psychomotor skills gained with simulator practice can become automated by the time the procedures are performed in real patients [107].

7.3. Transfer of skills

Skill transfer, that is, significant improvement in operative performance after a period of dedicated skills training, has been demonstrated following VR training in laparoscopy [108,109]. Recent evidence of skills transfer using VR simulation for endovascular skills training is encouraging. Berry et al [62] demonstrated improvements in both combined global rating scale and task-specific checklist after repetitive practice in both the porcine and VR groups. Improvement was shown to transfer from the VR simulator to the porcine model. Only one randomized trial in the endovascular field has examined skills transfer from the VR to the OR [63]. Surgical residents with no prior endovascular experience were enrolled. All participants received the same didactic introduction and were randomized to receive either mentored simulation training (maximum 2 hours) on a standardized iliofemoral angioplasty/stenting model or no simulation training. The simulator-trained group received significantly higher ratings on a supervised real iliofemoral procedure compared with the control group. Large randomized controlled trials need to determine whether simulated training in other endovascular procedures also translates into improved skills and if these skills are maintained over time.

7.4. Performance benchmarks

Simulator-derived performance reporting allows the learning curve of an individual trainee to be tracked. Practice can continue until a predetermined benchmark level of skill (based on the median performances of highly experienced physicians in the field) can be demonstrated. Further work is required to define appropriate benchmark levels of skill both within VR simulation and in vivo. Personalized training such

as this may be a more effective way of training than under-taking a set number of repetitions, and is known as proficiency-based training [109].

Successful incorporation of simulation into residency programs is dependent on the effectiveness of the curriculum. Although a particular simulator may be associated with numerous facets of validity, it is the curriculum that dictates how rapidly trainees will learn [29]. The curriculum ultimately dictates how effective a particular simulator will be in providing clinically relevant and useful skills. An effective skills curriculum should encompass goal-oriented training; a cognitive component; deliberate, distributed, and variable practice with appropriate methods for instruction and feed-back; an amount of overtraining and maintenance training; and sensitive and objective metrics for measuring skill profi-ciency [50].

8. Example of a comprehensive vascular skills training program

At the Louisiana State University Health Science Center–New Orleans, the Fundamentals of Vascular Surgery Symposium is held annually for integrated vascular surgery residents from around the United States. The pilot program for the open skill testing (FVS) occurred in October 2012 and has been held annually since then. The goals of the course are twofold:

1. For vascular surgery residents: With a faculty to resident ratio approaching 1:1, attendees spend 3 days receiving hands-on instruction in vascular techniques. Special emphasis is placed on procedures less commonly per-formed during residency, such as open thoracoabdominal aortic approaches, subclavian/tibial vessel exposures, and complex endovascular procedures.
2. For program directors: Using vascular skill assessment models, the course faculty spend hours observing and grading each attendee. This feedback is provided directly back to the program director. These outside assessments of residents' skill are a unique and valuable resource for portfolio building, milestone development, and individu-alized simulation curriculum design.

The course curriculum includes instruction (fresh cadaver laboratory, endovascular skill stations, open skill stations, didactics) and assessment (FVS, FEVS). There are also oppor-tunities for simultaneous teaching and assessment ("Suturing with the Experts," planning stations for endovascular aneu-rysm repair measurement). Table 3 lists the basic vascular surgery skills that were evaluated. Course content has been adjusted based on attendee feedback. Most notably, increasing the cadaver content, shortening the formal didactic sessions, and providing more hands-on instruction and im-mediate feedback.

As a measure of educational effectiveness, all residents complete a pre- and post self-assessment of confidence in nine vascular skills. Pooled results from the first 3 years demonstrated a statistically significant improvement in each proficiency, including Performance of Carotid Stent ($P < .05$), Thoracoabdominal Aorta Exposure ($P < .001$), and

Endovascular Aneurysm Repair Planning Based Upon Computed Tomography Angiography Measurement ($P < .01$). All attendees (100%, 48/48) reported being either "very" or "extremely" satisfied with the education experience. Ques-tionnaires were sent to each program director after the course and a 93% (28 of 30) response rate was achieved. All reported being either "very" or "extremely" satisfied with the skill as-sessments generated by the course, and 96% of the responders (27 of 28) felt the reports would be useful in helping the resi-dency program address the attendees' strengths and weaknesses.

From this experience, the following components are useful in creating a valuable vascular surgery simulation course:

1. High faculty-to-attendee ratio (minimum 1:2)
2. Low attendee-to-simulation station ratio (maximum 2:1)
3. Large fresh cadaver component
4. Emphasis on procedures rarely performed during vascular training
5. Limited didactics
6. Focused individual skill training and feedback to attendees
7. Focused individual skill assessment and feedback to pro-gram directors

In the founding year, as well as subsequent meetings, in-dividual surgical trainees completed three vascular skill assessment models, each under the observation of two experienced assessors blinded to their training level. Two models were designed to simulate an end-to-side anasto-mosis (ES) and a patch angioplasty (Patch). A third model required suturing around a clock-face (CF) design printed on patch material (Figs. 10 and 11) to emulate radial suturing as would be performed on a proximal aortic anastomosis. The model is placed in a clear plastic tube to simulate the depth of the abdominal cavity (Fig. 12). Trainees are given 5 minutes to perform the task of suturing around the entire "clock" with a 3-0 SH suture. Residents' scores on this simulation correlate strongly with their operative experience (Spearman's $\rho = .789$, $P < .001$). Benefits of the CF model include its relatively low cost and ease of transport, allowing trainees to practice away from the hospital.

ACGME log experience was recorded. Secondary evalua-tions of all three finished models were then performed by four blinded assessors. Inter-rater reliability among the seven as-sessors was high (Cronbach's $\alpha = .93$). Evaluations acquired by direct observation correlated well with participants' training level/experience for all three models (ES: $r = .85$, Patch: $r = .71$, CF: $r = .82$). Highest correlation with training level/experience was obtained with a combined score for each participant incorporating all observed ratings on each model ($r = .93$). Evidence for construct validity was collected by demon-strating each model's ability to discern junior (pre-MD to postgraduate year 2) from senior (postgraduate year 3 to 5) trainees (ES: $P < .005$, Patch: $P < .05$, CF: $P < .001$). Internal consistency was confirmed for each participant on all three models (Cronbach's $\alpha = .89$). Finished product evaluation demonstrated fair to poor correlation with training level/experience (ES: $r = .51$, Patch: $r = .53$, CF: $r = .24$). These results supported construct validity for three vascular skill assess-ment models. The data also demonstrate that the most

Table 3 – Basic vascular surgery skills.
Skill
Performance of ankle brachial index and vascular physical examination
Interpretation of noninvasive vascular laboratory studies
Ultrasound-guided percutaneous vascular access
Ultrasound assessment of venous conduits
Identification of basic vascular instruments
Basic technique for vascular anastomoses
Radiation safety and fluoroscopy
Basic catheter skills
Interpretation of vascular imaging studies

accurate assessments are obtained by direct observation with trained evaluators.

The FEVS model was developed in both silicone and VR versions. Twenty individuals (with a range of experience) performed four tasks on each model in three separate sessions. Tasks on the silicone model were performed under fluoroscopic guidance, and electromagnetic tracking captured motion metrics for catheter tip position. Image processing captured tool tip position and motion on the virtual model. Performance was evaluated using a global rating scale, blinded video assessment of error metrics, and catheter tip movement and position. Motion analysis was based on derivations of speed and position that define proficiency of movement (spectral arc length, duration of submovement, and number of submovements).

Performance was significantly different between competent and noncompetent interventionalists for all three performance measures: motion metrics, error metrics, and global rating scale. The mean error metric score was 6.83 for noncompetent individuals and 2.51 for the more experienced group ($P < .0001$). Median global rating scores were 2.25 for the noncompetent group and 4.75 for the competent users ($P < .0001$). The FEVS model successfully differentiated competent and noncompetent performance of fundamental endovascular skills based on a series of objective performance measures. Furthermore, it was demonstrated that performance on a replica VR model correlated to performance on the physical model, lending further support to the validity of this platform. This model has been proposed to serve as a platform for skills testing for all trainees, and multi-institution trials of both models are underway.

Despite the success of simulation-based training and assessment in vascular surgery, major shortcomings of simulation as a training device remain. First, the assessment tools have been adapted from Resnik's OSATS model for evaluation of surgical skill without rigorous validation. A recently published review of studies assessing vascular surgical performance found that 84% pertained only to the
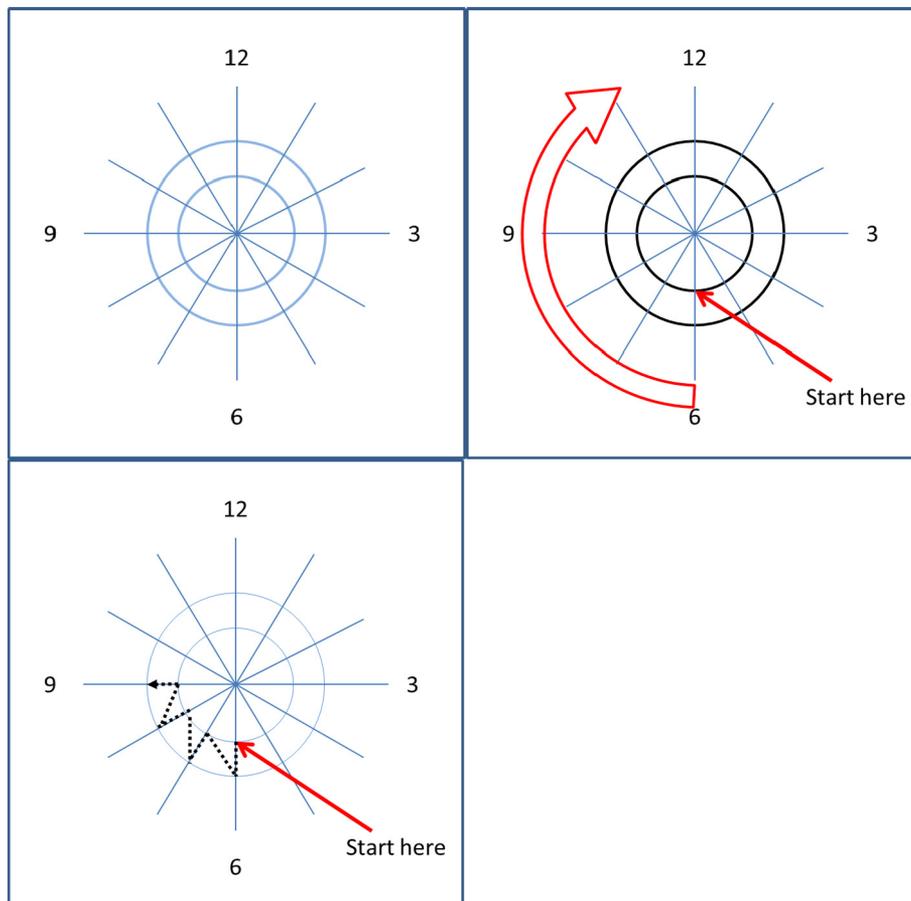

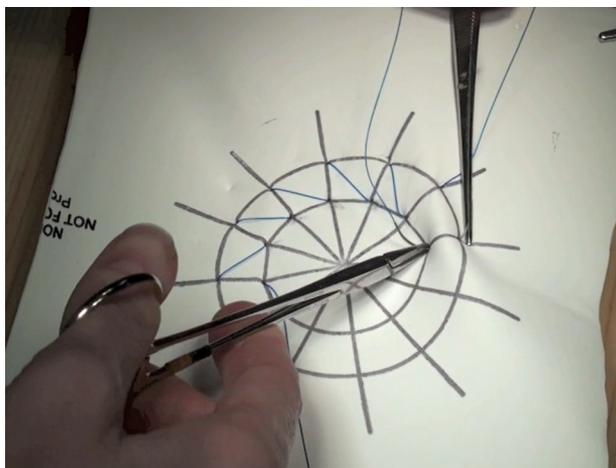Fig. 10 – Louisiana State University clock face model instructions.

Fig. 11 – Louisiana State University clock face model demonstration.

simulated environment and that, while existing assessment tools may be relevant to individual technical skill acquisition, a generalizable tool has yet to be developed or validated, and practical assessment of resident readiness to operate remains elusive. Houston Methodist Hospital has sought to meet this need with the validation of the Global Rating Assessment Device for Endovascular Skill (GRADES) in the live operating room setting, but, clearly, further assessment tool development will be required to meet the need described by Mitchell. Cost has also traditionally posed a significant challenge to widespread access to vascular, especially endovascular, simulation-based platforms. At anticipated costs of less than $5000 for both the endovascular and open vascular simulation models used in FVS and FEVS, these models will be financially accessible to most educational program.

Despite this rather low cost of entry, simulation for most users is often still viewed as an isolated tool without a well-described means of implementation. Like simulation centers in general surgery, vascular simulators are often left largely

Fig. 12 – Plastic tube in which the clock face model is secured to simulate the depth of the abdominal cavity.

unused due to constraints of faculty time and lack of curriculum for standard use. This notion helps perpetuate perhaps the largest obstacle facing the use of simulation-based training, which is skepticism about its ability to directly translate into operating room skill and measurable patient outcomes. To overcome this obstacle, the Fundamentals of Vascular Surgery Task Force was formed by the Association of Program Directors in Vascular Surgery to work through the implementation of a standardized simulation testing and skills curriculum. Among the goals of the task force are the development of standardized open and endovascular skill testing, the resolution of cost issues, the integration of simulation into vascular training curricula, and identifying adequate assessors.

9. Future studies

The intent of simulation training is to shorten and flatten the learning curve for real procedures. To date, no studies have objectively investigated the degree to which VR endovascular simulators satisfy this demand. Research needs to be conducted, similar to that performed in the airline industry and laparoscopic field, to calculate the transfer-to-effectiveness ratio for vascular simulator-based training curricula [110,111]. Transfer-to-effectiveness ratio is the difference in number of trials or time taken to achieve performance criterion (in the air) between untrained and simulator-trained pilots divided by total training time received by the simulator-trained group. This ratio allows you to calculate how time-effective the addition of a simulator would be in a training program in relation to initial outlay costs. Ratios >0.5 to 1.0 are achieved by training programs containing modern flight simulators and 2.28 by proficiency-based training curricula including laparoscopic simulators [112].

Credentialing and certification of surgeons as part of continuing education is not a new concept. Currently, the American Board of Surgery utilizes the six core competencies established by the ACGME for their Maintenance of Certification program. This program insists on continual learning over time. To ensure Maintenance of Certification, physicians need to demonstrate (1) evidence of professional standing through maintenance of an unrestricted license, hospital privileges, and satisfactory references; (2) evidence of commitment to lifelong learning through continued education and periodic self-assessment; (3) evidence of cognitive expertise based on performance on a secure examination; and (4) evidence of evaluation of performance in practice, using tools such as outcome measures and quality improvement programs, and evaluation of behaviors such as communication and professionalism [50].

Although technical skills training and simulation are not part of the American Board of Surgery Maintenance of Certification program, future studies in this area would be important. Research conducted on more senior learners with limited endovascular skill is needed. Simulation could potentially play an important role in the re-entry of these physicians into mainstream practice and maintenance of technical skills for "certification." Physicians who have

completed training may benefit from continuing education and simulator-based training to support their continued learning and improvement of cognitive and technical skills. Repetition, self-assessment, and the opportunity for feedback are the cornerstones of deliberate practice, as defined by Ericsson et al [91,92].

Similar to athletes and musicians, physicians may benefit from "warming up" on a simulator before an elective procedure. The opportunity for endovascular therapists to practice complex endovascular procedures before performing them in the actual patient is currently being evaluated. Imagine a patient with a symptomatic CAS, challenging anatomy, and high anesthetic risk. The software PROcedure Rehearsal Studio (Simbionix, Cleveland, OH) rapidly loads the patient's computed tomography scan data from a CD onto the simulator and generates a digital three-dimensional model of the patient's clinically relevant anatomy from the scan data; subsequently, a simulated interventional environment is created. This enables interventionalists to try different approaches with a range of endovascular tools before treating the actual patient [113]. This technology is indeed exciting and may have an impact on health economics (reduction in operating and fluoroscopy time, number of tools reduced, cost of the procedure) and eventual outcomes for the patient.

The importance of teamwork in preventing medical error is well recognized [114,115]. Future research aims to enhance nontechnical skills of both physicians and teams by simulator-based training. A virtual interventional suite allows the endovascular therapist and the interventional team (anesthetist, radiographers, theatre nurses, and angiography suite nurses) to work in a realistic environment on simulated tissues. They can be exposed to complex or rare life-threatening events and learn how to manage crises situations in a simulated interventional suite allowing feedback by knowledgeable instructors without exposing patients to risk [75,116].

10. Conclusions

As evidenced by this article, much work has been done by educators in advancing our understanding of the role simulation can play in vascular training. In the era of rapidly expanding technology, shorter vascular training paradigms, and ever-increasing public scrutiny of surgical outcomes, vascular and endovascular simulation centers have great potential for improving the training of the next generation of vascular specialists. A structured curriculum with competency assessment needs to be developed, and consideration for formal skills testing should also be provided, similar to those implemented in FLS and FES.

Although most vascular surgery trainees now have some exposure to simulation-based training, there remains a lack of a practical curriculum for implementation. New training paradigms and an ever-evolving field mandate that we identify, teach, and assess the essential skills required for practicing vascular surgery. The pathway to a formal vascular skills examination is long and arduous but certainly achievable.

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